LER-LHC Instability Issues

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- LER vs SPS, VLHC, Tev
- Instabilities:
  - -TMCI
  - - Space-charge
  - - RW Coupled bunch
  - - AC tuneshift
  - - e-cloud
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- Summary

Parameter Set: LER vs SPS

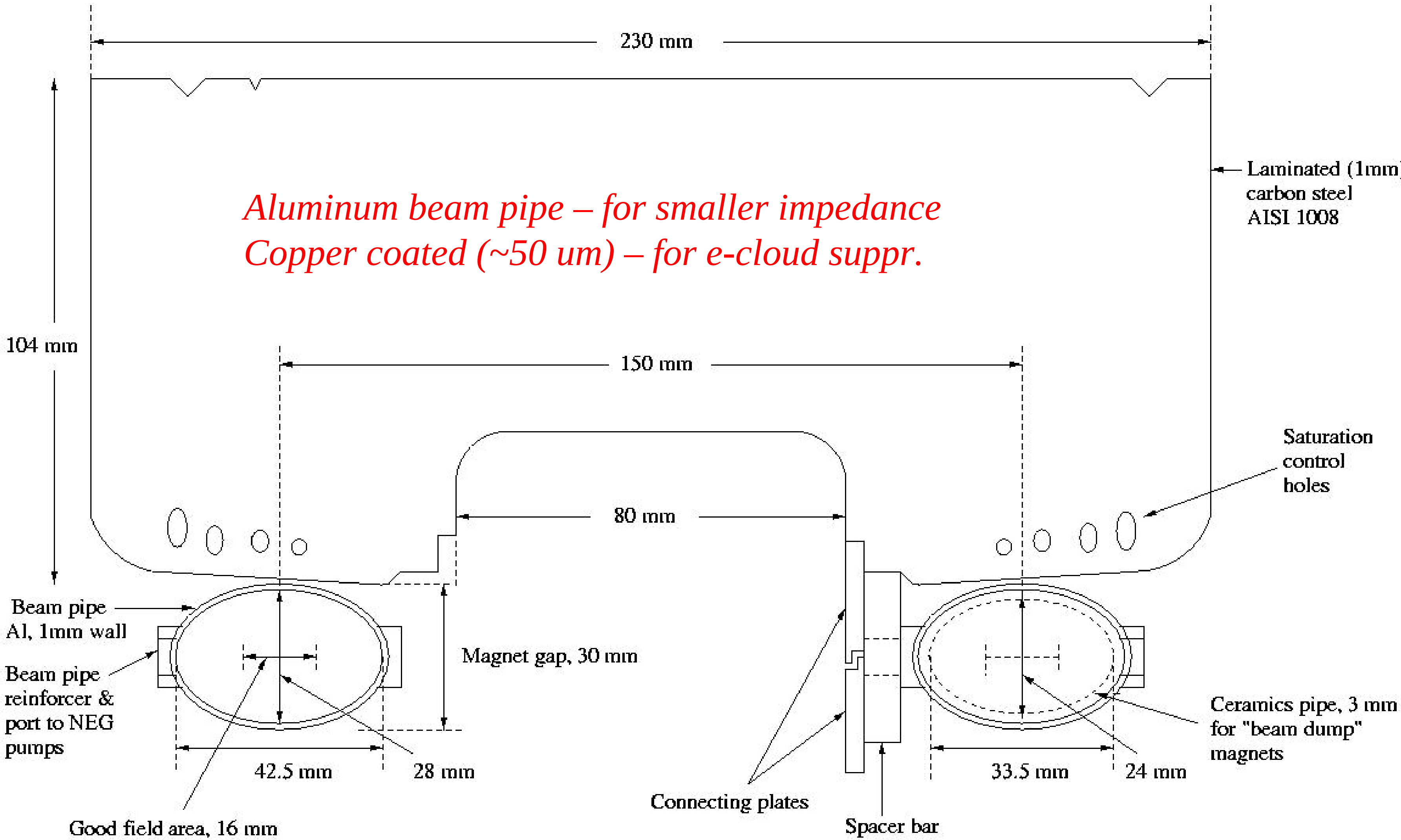
Parameter	Units	T.Sen, this Workshop LER	SPS
Inj./top energy	E inj/top, TeV	0.45/1.5	0.026/0.45
Circumference	C, km	26.659	6.916
Bunches/buckets	B, h_{RF}	2808/35640	288/4620
P/bunch	N_p, 10**9	115	115
Tune	ν	64.31/59.32	~26.6
Slip factor	η	0.00032	0.00186
Beta av/max/min	β, m	66/182/31	~41
Pipe ½ size	a/b, mm	14/21	22.5/70
Transv. Emitt	$\varepsilon_{T,}$ π urad, rms	3.5	3.5
Ave/bunch current	I_B, mA,/I_b, mA	580/0.2	230/0.8
RF frequency	f_{RF}, MHz	400	200/800
RF Voltage (inj)	U_{RF}, MV	8	4/1
Synchr. tune (inj)	ν_s	0.0031	0.0069
Bunch length (inj)	σ_s cm, rms	13	110
Dp/p, rms (inj)	dP/P	0.0003	0.007

LER Magnet and Beam Pipe

LARP

H.Piekarz, this Workshop

Aluminum beam pipe – for smaller impedance
Copper coated (~50 um) – for e-cloud suppr.



Head-Tail Instability in Tevatron

Amplitude of the dipole moment vertical oscillations for the head-tail mode with monopole longitudinal configuration at the negative chromaticity (max 4-10 mm)

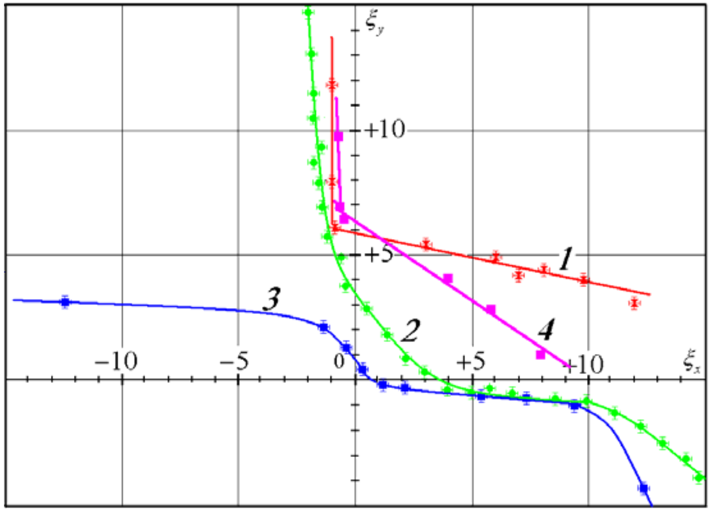
$\xi_y \approx -3$

$l_s = 0$

$N_{ppb} \approx 2.6 \cdot 10^{11}$

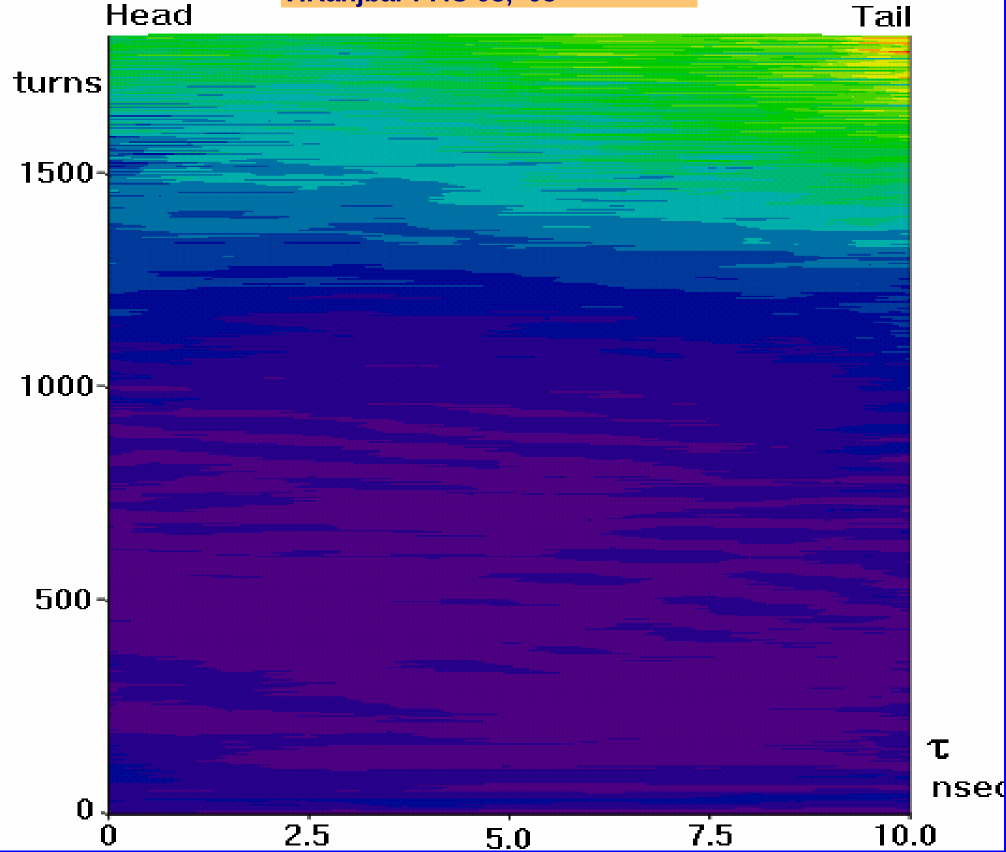
E=150 GeV

Stability regions vs Vert and Hor Chromaticities: before – 1 and after - 3 Screening injection Lambertsons



P.Ivanov, V,Shiltsev PAC'05

V.Ranjbar PAC'03, '05

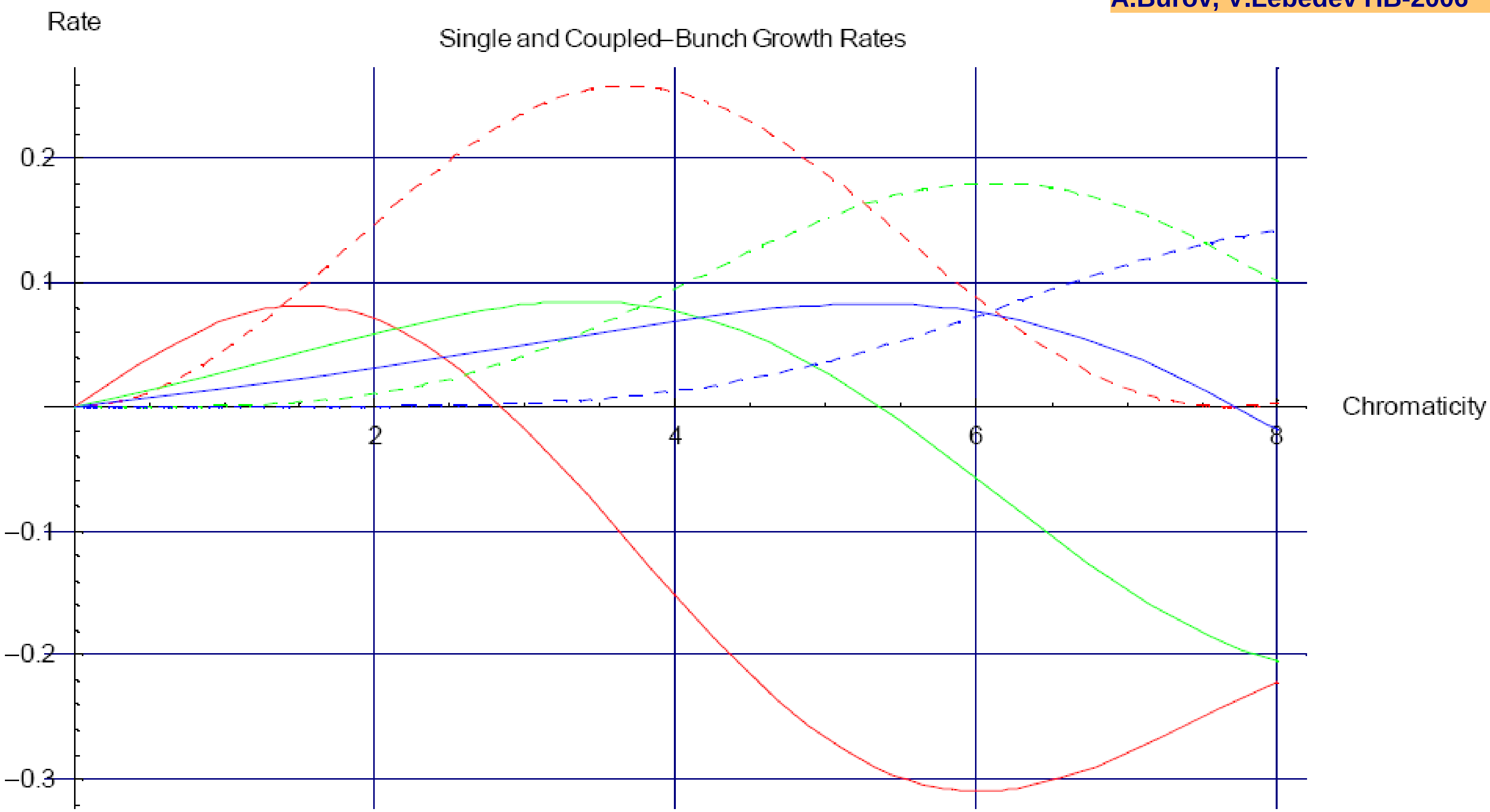


There are many head-tail modes…

$$\Lambda_l^s = -\frac{N_b r_0}{2\pi Z_0 \gamma \nu_\beta} \int_{-\infty}^{\infty} d\omega \, \mathrm{Re}\, Z(\omega) J_l^2(\omega \hat{z}/c - \chi)$$

- Single (solid lines)- and Coupled-Bunch (dashed) growth rate contributions are shown in the figure below for *l=1* (red), *l=2* (green) and *l=3* (blue), $\mu = \mu_0$.

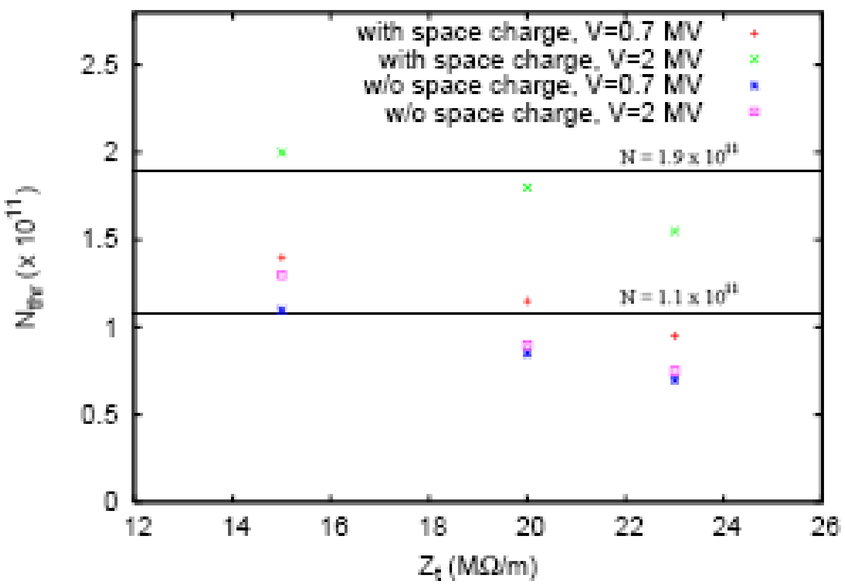
A.Burov, V.Lebedev HB-2006



Head-tail in SPS

Single bunch limitations in the SPS: TMCI

TMCI thresholds for LHC bunch at 25 GeV, $\xi = 0$



(*G. Rumolo et al., HEADTAIL, 2005*)

- **Fast transverse instability:** observed in 2002 at 25 GeV. $N_{th} = 1.2 \times 10^{11}$ for $\varepsilon = 0.3$ eVs, τ=3.6 ns, V=0.6 MV, $\varepsilon_{H,V} = 1\ \mu$m (*H. Burkhardt et al., 2003*)
- Cure by high chromaticity and high voltage (slow beam loss?)
- Flat top: $N_{th} = 1.9 \times 10^{11}$ for ε=0.3 eVs.
- **Low threshold** for 4 more MKE kickers installed $\rightarrow$ screening (*F. Caspers, E. Gaxiola et al.*)

E.Shaposhnikova, Arcidosso'05

Weak/Strong Head-Tail Instability

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"Strong head-tail" occurs at zero Q' , in contrast to "weak head-tail" which depends on chromaticity. Frequencies of coherent bunch motion (mode 0) and head-tail motion (mode 1) are shifted by transverse wide-band impedance toward each other. Above a threshold the frequencies become equal and instability occurs with characteristic growth time of a fraction of synchrotron period (see cartoon and figure).

The TMCI due to RW impedance (LF) has a threshold of:

$$N_{thr} = 1.85 \cdot 10^{10} \cdot \frac{E_{inj}}{1\,TeV} \cdot \frac{\nu_s}{0.01} \cdot \left(\frac{a}{9\,mm}\right)^3 \cdot \frac{232\ km}{C} \cdot \frac{250\ m}{<\beta>} \cdot \sqrt{\frac{\sigma_s}{10\ cm}}$$

$\xi(dP/P)$

Protons/bunch, $N_p/10^9$	115	
LER TMCI Threshol	770	a=14mm
SPS TMCI Threshold	260	

*not taking into account impedance coming from kickers, lambertsons, bellows, RF, BPMs (i.e. "not Resistive Wall")

Space Charge is not a problems for LER dQ=2e-4

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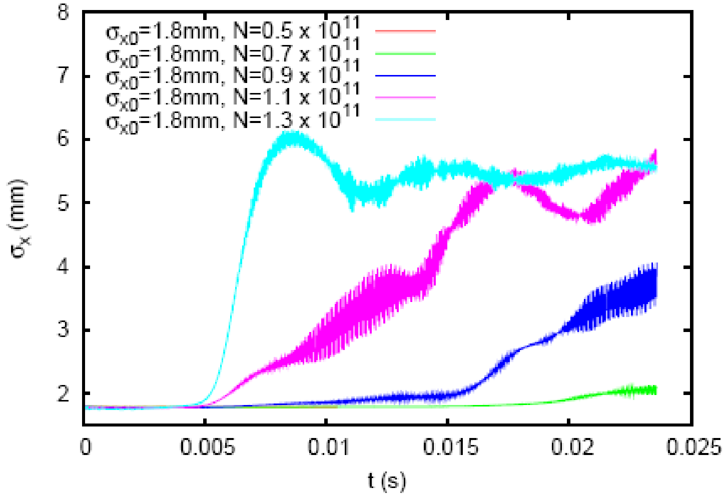
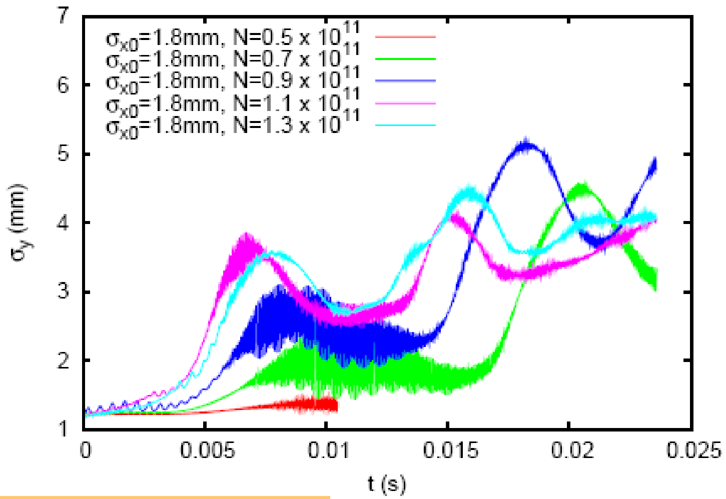
…while it is a problem in SPS at injection:

Single bunch limitations in the SPS: space charge





- **Increases the TMCI threshold, but causes emittance blow-up** (*G. Rumolo et al., 2005*. **Simulations at 25 GeV with** $Z_t = 15$ **M**Ω**/m,** $\varepsilon = 2.5$ μ**m).**
- **Tolerable space-charge tune spread:**
  - **PSB:** $\Delta Q_{sc} < 0.5$
  - **PS:** $\Delta Q_{sc} < 0.3$
  - **SPS:** $\Delta Q_{sc} < 0.07$ **(ppbar limit)**
- **SPS:** $\Delta Q_{sc} = 0.05$ **(0.07) for nominal (ultimate) LHC intensity**
- **Recent measurements in the SPS: beam loss** $(1.2 \rightarrow 0.8) \times 10^{11}$ **for** $\Delta Q_V = 0.3$**, lifetime 50 s for** $\Delta Q_{H,V} = 0.14, 0.24$ (*H. Burkhardt et al., EPAC'04*).

E.Shaposhnikova, Arcidosso'05

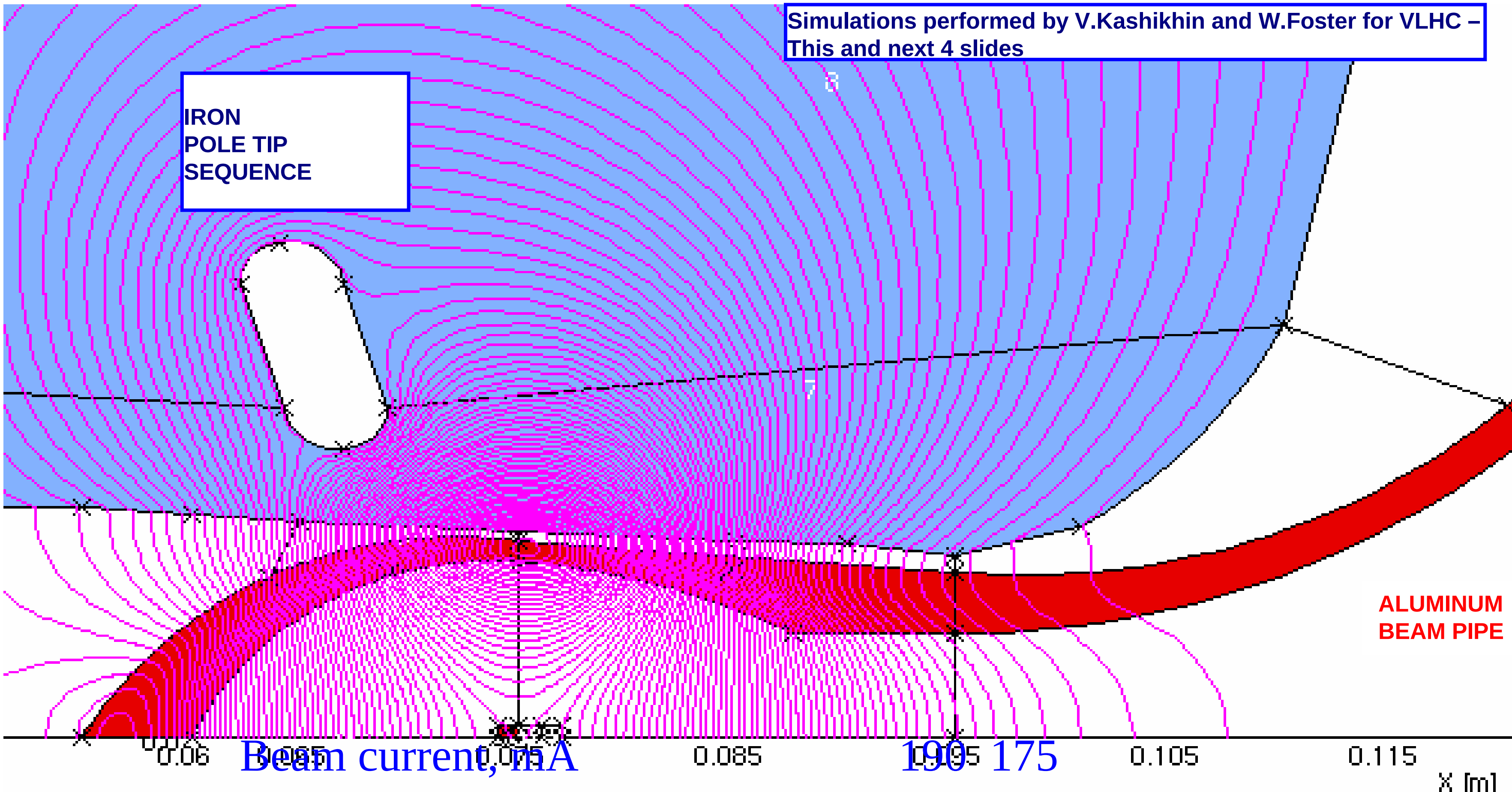
Resistive Wall Coupled Bunch

This effect is proportional to the total beam current and is driven by the low-frequency transverse impedance due to final conductivity of the beam pipe walls. Instability growth time in number of turns is

$$N^{RW} := \frac{E_{inj}\, a^3}{eI_B\, Z_0\, \beta} \cdot \sqrt{\frac{2\,\pi\,\Delta\nu_\beta\,\sigma_{Al}}{cR^3}}$$

LER	I_b=580mA	N_rw=52 turns
SPS	I_b=230mA	N_rw=69 turns

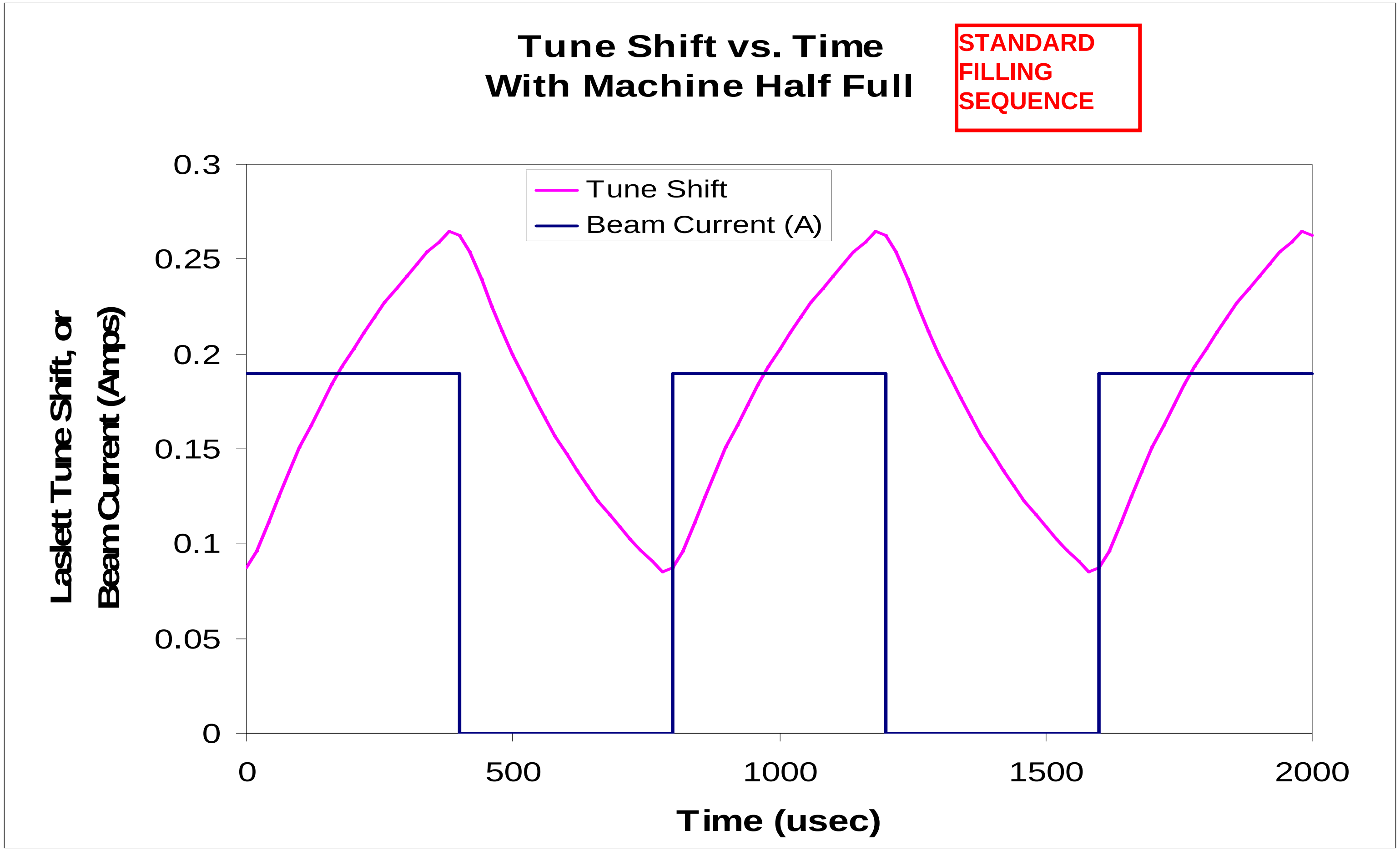
Image currents → Laslett tune shift



Beam current, mA	190	175
RW increment, turns	0.54	56

Magnetic field distribution caused by beam pipe eddy currents following ten 20 μsec bunches with current 0.19 A. It is predominantly a quadrupole field. This field is normally superimposed on the much larger main dipole field of the magnet.

dQ has DC and AC components …

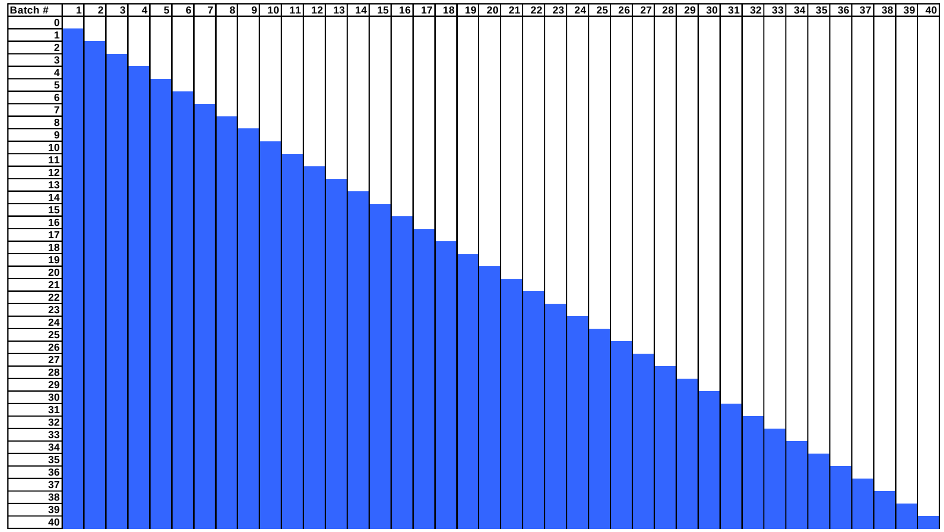


Laslett Tune Shifts with Stage 1 VLHC Half Full: Standard filling sequence for which the beam current is a 50% duty cycle square wave when the machine is half full. This generates a large AC component to the tune shift.

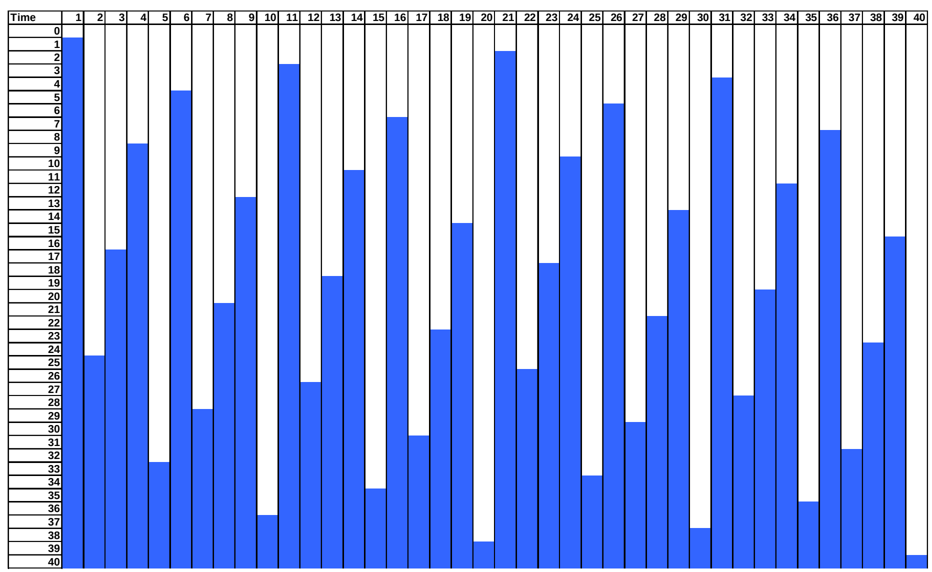
Standard vs Optimal Loading pattern

LARP

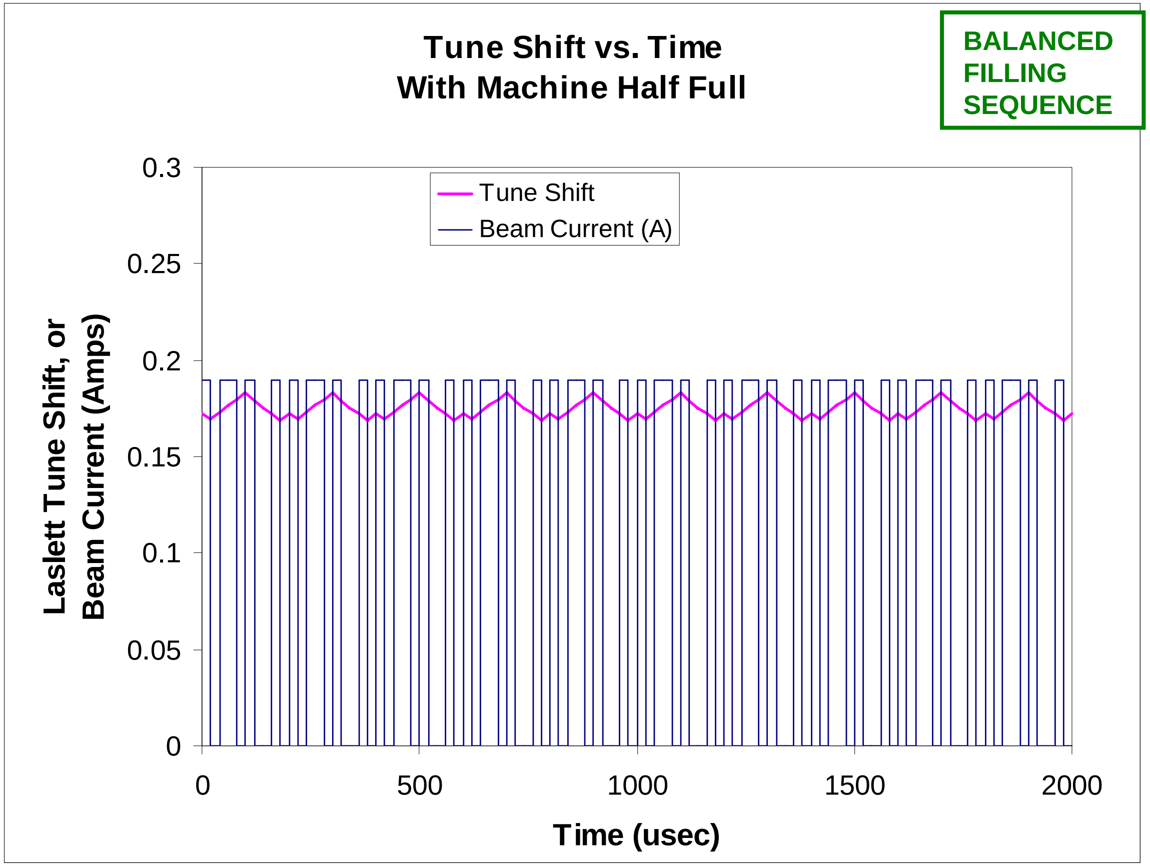
STANDARD FILLING SEQUENCE



BALANCED FILLING SEQUENCE

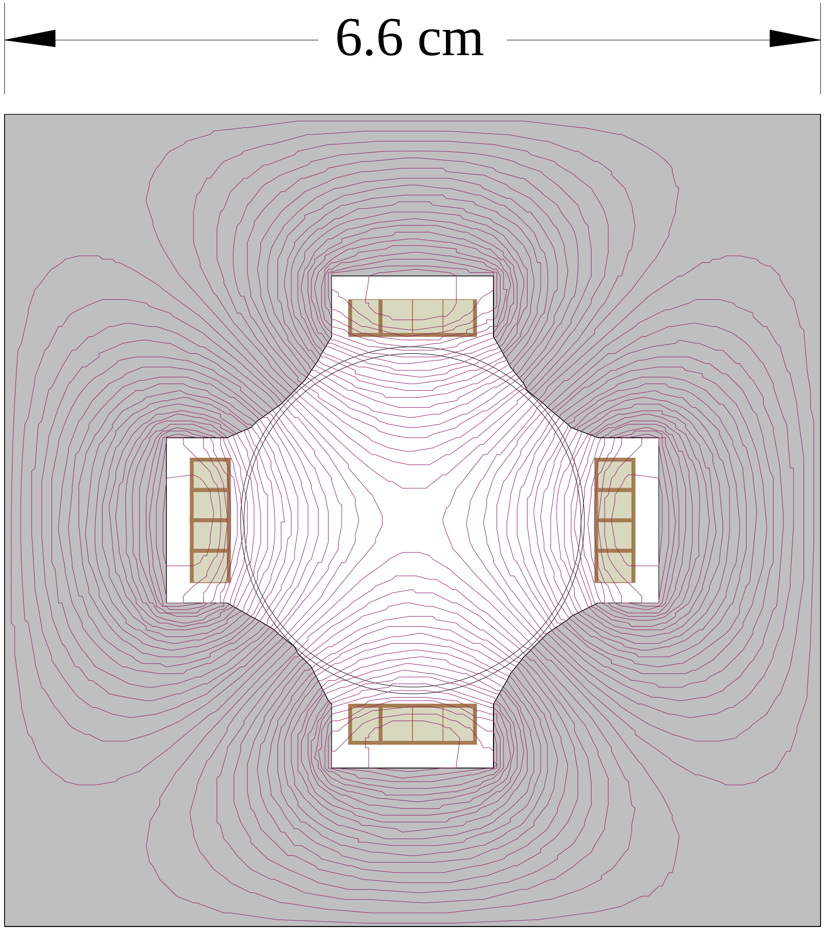


…dependent on current loading…



Balanced filling sequence which spreads the charge evenly around the circumference and yields a smaller AC component to the tune shift. Filling is in units of 20usec "batches" from the Tevatron. A total of 40 batches are required.

Compensate remaining dQ → AC quads



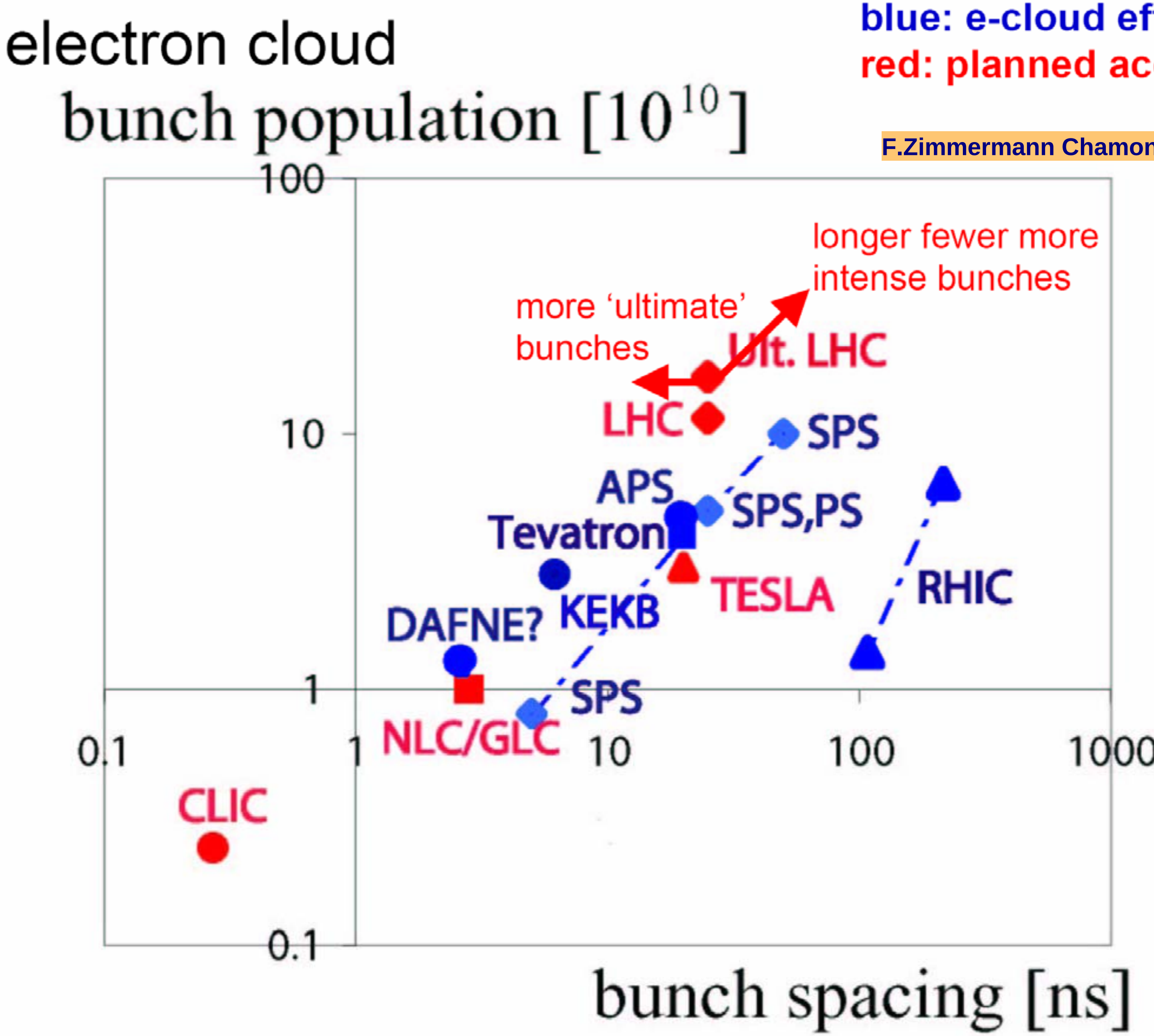
Laslett Correction Quad Parameters	
Gradient	1.55 T/m
Length	0.3 m
Number Required	2
Width, Height	6.6 cm (square)
Beam Pipe	28mm Round SS
Operating Current	±62.5 Amps
DC Resistance	0.011 Ohm
RMS Power (Ohmic)	~20 W
Number of turns	2/pole
Inductance	18.8 μH
Rise Time (0-100%)	30 μsec
Inductive Voltage	± 39 V
Pole Tip Fields	0.025T
Magnetic Material	Ferrite

Laslett Correction Quadrupoles: Cross section and parameters.

Electron Cloud

blue: e-cloud effect observed
red: planned accelerators

F.Zimmermann Chamonix -?? (2004?)



experience at several storage rings suggests that the e-cloud threshold scales as $N_b \sim L_{sep}$;

possible LHC upgrades consider either smaller L_{sep} with constant N_b, or they increase L_{sep} in proportion to N_b 24

Beam Stability Comparison Table

	LER	SPS	TeV	VLHC
TMCI e9 N_{thr}/N_{nom}	770/115	260/115	1500/300	28/25
Space-charge dQ	0.0002	0.05	0.001	0
Res Wall N_{turns}	~50	~70	1800	1
AC tune e-3 max/comp	24/2	3	0.4	200/20
E-cloud wrt SPS	~1	1	0.12	0.3

Possible Cures/Improvements

- TMCI and weak-head tail
  - running at higher Q' for short time should not hurt much
  - Cu or Ag coating → x1.3
  - Tev-like b-by-b feedback will help to x2
- Electron cloud
  - Cu coating and Scrubbing
  - Ribbed or scratched surface
- Coupled bunch
  - can be suppressed by FB system
  - even at x2 the intensity
- AC tune shift of 0.024 is unacceptable
  - needs "wise" loading
  - or AC quad

Summary

- Instability-wise, LER-LHC is somewhere in between Tevatron (not much of trouble) and VLHC (a lot of trouble)
  - Comparable to SPS in
    - Resistive Wall coupled bunch
    - e-cloud
  - have potential advantages in
    - Space-charge
    - TMCI and weak-head tail
  - significantly higher AC dQ can be compensated by "wise" loading pattern
- With certain cares, LER-LHC may be able to handle twice the bunch/total current:
  - a=14 mm Al(Cu, Ag) beam pipe is a must
  - Other impedances have to be minimized

Resistive Wall Coupled Bunch

- Coalescing at top energy 2→9
  - Thin Cu, Ag coating 1.3
    - Asymmetric beam pipe 1.5→3
  - RF quadrupole 5
  - AC chromaticity 5→10
  - Feedback system 5→more

Feedback Systems for LER

FB to damp resistive wall coupled bunch
and injection errors: high gain
narrow band 100 kHz

Wide-band FB to damp the rest of
bunch to bunch modes: one turn delay
26 MHz band (2/bunch spacing)

•Head –tail (TMCI) feedback: small gain

mode 0: band 26 MHz
mode 1: bandwidth 3 GHz

FB to suppress emittance growth
•Longitudinal feedbacks